

## The New (Version 4) Calibration of the Nighttime 532nm Channel of the CALIPSO Lidar\*

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\*This paper is dedicated to the memory of W. Hunt.

### 25 **Abstract.**

The data products from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on board  
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) were recently  
updated following the implementation of a new (version 4.1) calibration algorithm for all the level  
30 1 products. We present the motivation for and the implementation of the version 4.1 nighttime 532  
nm parallel channel measurements. This is the most fundamental calibration of CALIOP data since  
all other measurements, i.e the 532 nm nighttime perpendicular, daytime 532 nm as well as 1064  
nm are tied to this calibration. The new calibration is shown to resolve the discrepancies in the  
earlier version and also leads to an improved representation of the stratospheric aerosols. Initial  
35 validation results using ground based and airborne lidar measurements are also presented.

## 1. Introduction:

There is currently a strong focus on understanding various aspects of how aerosols and clouds impact climate change processes as well as on their mutual interactions (IPCC, 2013). A global perspective is required in view of the long distance transport of aerosols and effect of clouds on large scale atmospheric dynamics. Despite nearly two decades of satellite remote sensing, the crucial vertical information on aerosols and clouds had been lacking. The space based lidar CALIOP on board CALIPSO has now been providing the first continuous measurements on the global vertical distribution of clouds and aerosols since 2006 (Winker et al., 2009). These measurements have been used by numerous authors over the last ten years and have greatly advanced our knowledge in the areas of cloud and aerosol physics. The fidelity of these results depend crucially on the calibration of the CALIOP lidar (Powell et al., 2009). The lidar transmits linearly polarized light at 532 nm and 1064 nm and measures attenuated backscattered light from the atmosphere including both parallel and perpendicular components at 532 nm and total backscatter at 1064 nm. These measurements are calibrated using the nighttime observations at 532 nm at stratospheric altitudes where aerosols and clouds have been assumed to be absent and where most of the backscattered light is from molecules which can be computed from an atmospheric model, e.g., the Global Modeling Assimilation Office (GMAO) GEOS5 model (Powell et al., 2009). This is the first and most important step in the CALIOP data processing as the daytime backscatter measurements at 532 nm as well as the measurements at 1064 nm are calibrated subsequently using the nighttime calibration. These calibrated attenuated backscatter data at 532 nm and 1064 nm constitute the level 1 in the CALIPSO data processing hierarchy which are then used for layer detection and retrievals of particulate extinction and backscatter retrievals (Vaughan et al., 2009, Young and Vaughan, 2009).

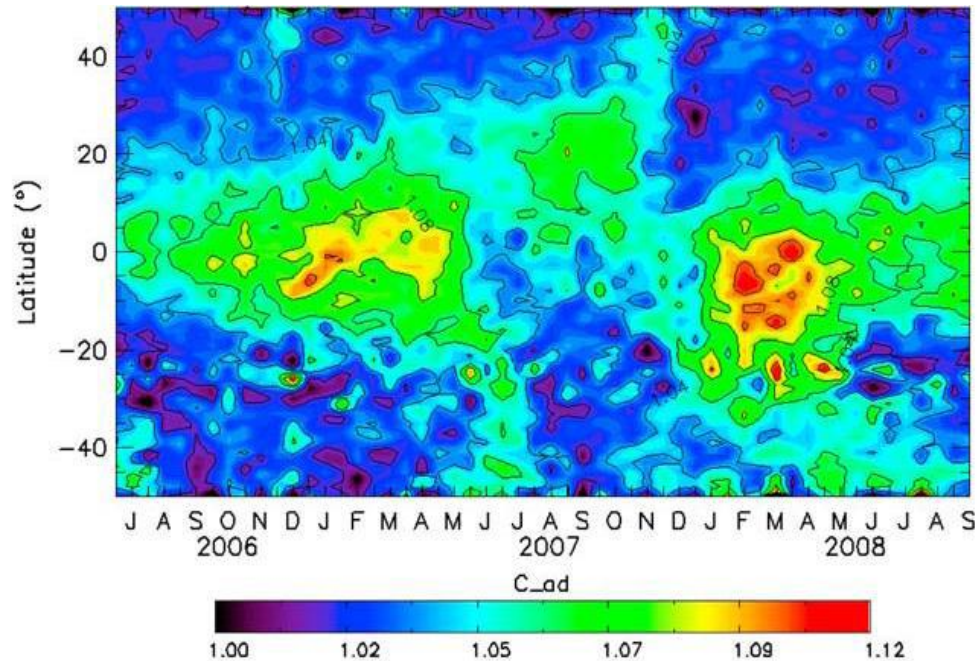
The molecular normalization was originally implemented between 30 and 34 km and remained unchanged in the subsequent versions of CALIPSO data up to version 3.30 (Powell et al., 2009). In recent years it has become clear that this region is not completely free of aerosols and thus the calibration needed to be improved (Vernier et al., 2009, Powell et al., 2009). In this paper we report the results of a new calibration algorithm for the nighttime 532 nm data which has been implemented for the new version 4.10 (V4) of CALIOP data and which was released in April 2014. In this new algorithm, the molecular normalization is now applied at 36-39 km where particulates are nearly absent. However, this altitude regime is near the limit of CALIOP detection range and thus has the attendant problem of significantly lower signal to noise ratio (SNR) necessitating more averaging of the data. Further an improved meteorological data set from MERRA 2 reanalyses is employed in the new version of the data. In this paper, we present the details of this new calibration as well as improvements in the new version as a result of these changes.

## **2. Motivation and implementation of the new (V4) calibration for nighttime 532 nm data**

### **2.1 The need for a new calibration**

The initial decision to calibrate the CALIOP nighttime 532 nm channel signals at 30-34 km was dictated by the need to have sufficient molecular backscatter to provide a robust SNR (required to be at least 50 averaged over 5 km vertically and 1500 km horizontally) as well as low or negligible contamination from stratospheric aerosol loading (Hunt et al., 2009). Vernier et al. (2009) analyzed the time sequence of attenuated scattering ratios (ratio of total attenuated backscatter and the molecular backscatter, SR) calculated from CALIOP 532 nm measurements over the tropics and showed anomalously low values ( $SR < 1$ ) above 34 km as well as in the lower

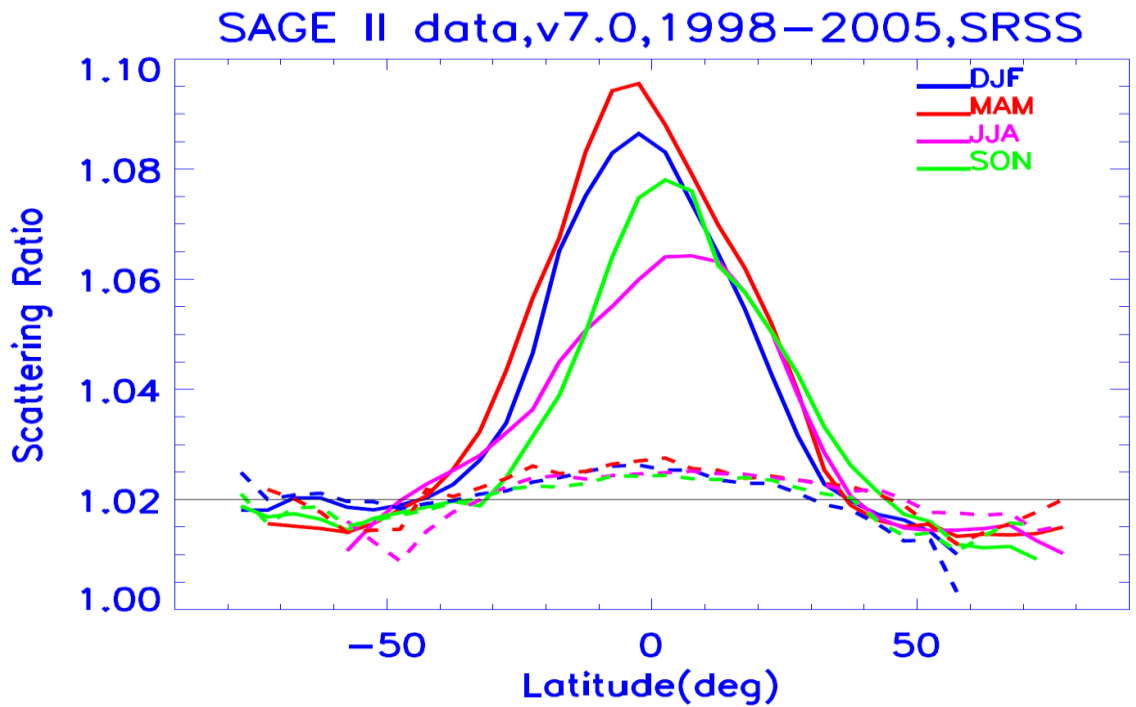
stratosphere. Since molecular normalization at 30-34 km implies SR should be one at these altitudes, this indicated an inadequate calibration in the CALIOP data. They adjusted the calibration by normalizing the SR values by calculated SR at 36-39 km. **Figure 1** (reproduced from Vernier et al. (2009)) shows the latitude time cross section of the adjusted calibration constant which effectively represents the revised aerosol SR at 30-34 km. As can be seen only minor adjustment is required in the mid latitudes, but there is ~ 2-12% underestimation in SR at 30-34 km in the tropics.



**Figure 1.** Zonally averaged time-latitude cross section of the adjusted calibration coefficient obtained using the CALIOP version 2 data (reproduced from Vernier et al., 2009).

A similar problem was noted by Powell et al. (2009) when they found a persistent dip in the tropics in clear air SR ( $< 1$ ) between 8-12 km, which also underscored the need for an improvement in calibration.

The most extensive and accurate measurements of stratospheric aerosols have come from the Stratospheric Aerosol and Gas Experiment II (SAGE II) instrument. SAGE II has provided the extinction coefficient profiles in the stratosphere using solar occultation technique from 1984 through 2005 (Mauldin et al., 1985, Thomason et al., 1997, Damadeo et al., 2013). Between 1991-5 1996 the stratosphere was loaded with volcanic aerosols from Pinatubo eruption and no meaningful data are available for that period. However, the stratospheric aerosol loading has remained near the background levels since 1998 except for some modulation by smaller volcanoes (Vernier et al., 2011).



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**Figure 2.** Scattering ratios estimated from the extinctions retrieved from SAGE II at 30-34 km (solid lines) and at 36-39 km (dashed lines).

**Figure 2** shows the zonal average of SR at 30-34 km (solid lines) and 36-39 km (dashed lines) as derived from the SAGE II extinction retrievals between 1998 and 2005 using the latest version 7.0 of SAGE II data (Damadeo et al., 2013). The aerosol extinctions at 525 nm from SAGE II have been converted to scattering ratios using a stratospheric aerosol lidar ratio of 50 sr; an Angstrom exponent of 1.6 was then used to convert the data from 525 nm to 532 nm (Khaykin et al., 2017). All the extinction data with estimated error less than 100% were included from both sunset and sunrise occultations. The data before 1998 were not used to avoid the contamination from the Pinatubo volcano. As can be seen, the SR for the background aerosols can reach as much as 7-8% at 30-34 km over the tropical latitudes while decreasing steeply to ~2% at the polar regions. Further, significant seasonal variation at these altitudes can also be seen with maximum extinction being in winter and lowest in summer. On the other hand at 36-39 km, the SR values are by and large uniform over all latitudes at about 2%, with very little seasonal variability. This result again suggests that there is a low bias in the CALIOP data in the V3 calibration algorithm and indicates that a better calibration with minimal aerosol contamination is needed. With more data acquisition and improved understanding of the quality of the data, it was realized that the calibration altitude can be raised to 36-39 km.

## 2.2 CALIOP 532 nm nighttime calibration method

The primary CALIOP nighttime 532 nm calibration algorithm uses the parallel channel measurements of the geolocated, range scaled and energy and gain-normalized signals (X) and is defined simply by the equation:

$$C = \frac{X(Z_c)}{\beta(Z_c) T^2(Z_c)} \quad (1)$$

$$\text{with } X(z) = \frac{r^2 S(z)}{E_0 G_A}, \quad (2)$$

$S$  being the measured signal after subtracting the solar background and digitizer offset voltages,  $Z_c$  is the calibration altitude,  $E_0$  the laser energy,  $G_a$  is the amplifier gain,  $\beta$  is the parallel backscatter coefficient from molecules and aerosols and  $T^2$  is the two-way transmission:

$$5 \quad T^2(z) = \exp \left\{ -2 \int_0^r \sigma [z(r')] dr' \right\} \quad (3)$$

Where  $\sigma$  is the volume extinction coefficient and is the sum of molecular scattering, aerosol scattering and ozone absorption coefficients. The latter are computed from a molecular model and accurate calibration of CALIOP nighttime 532 nm data depends crucially upon this model. In the past versions up until V4.0, CALIOP calibration algorithm had used the molecular and ozone  
10 number densities from the NASA GMAO models. These model parameters keep getting updated with improvements in the inputs and the assimilation system and successive versions of GMAO models were used for different versions of CALIOP data. For V4.10 the latest Modern Era Retrospective Analysis for Research and Applications version 2 (MERRA 2) model from GMAO has been adopted (Molod et al., 2015). Apart from the general improvements, MERRA 2 for the  
15 first time assimilates aerosol information from various satellite and ground based measurements and the aerosol radiative feedback to the atmospheric fields. The estimation of the 532 nm parallel channel calibration co-efficient is carried out using equation (1) assuming that there is no aerosol in the calibration region. Even with this assumption, the calibration procedure involves significant filtering and averaging of the measured signals. These are briefly described in the following  
20 sections.

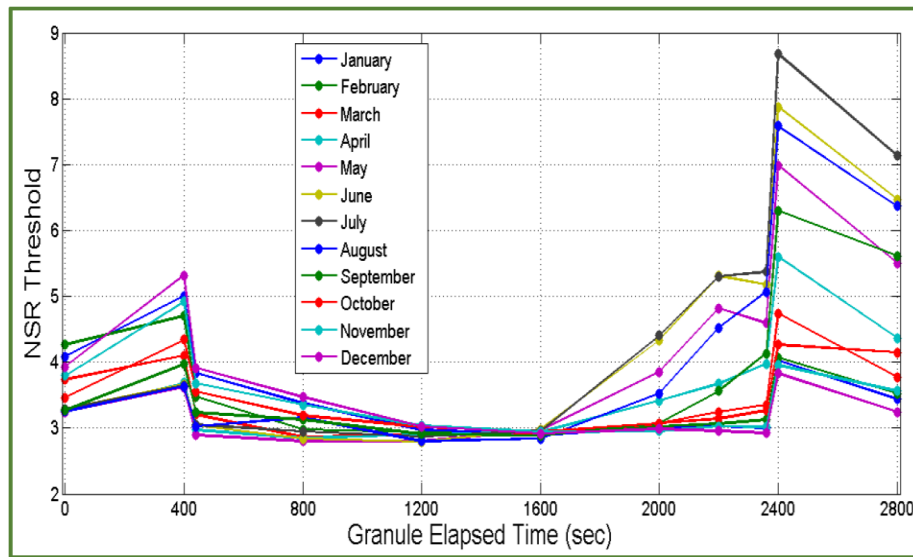
### 2.3 The new spike filter

As described in Powell et al. (2009), the lidar signal profiles are carefully filtered in a three-step process in order to eliminate the large noise spikes often encountered in the calibration region before using them in the subsequent averaging scheme leading to the computation of the calibration coefficient. These large noise spikes occur particularly over an extended area over the continent of South America and adjoining South Atlantic Ocean and is known as the South Atlantic Anomaly (SAA) where high energy charged particles from the Sun and cosmic rays trapped in the Van Allen belts come down to low altitudes and affect the CALIOP sensor leading to the noise spikes. In the first step, an adaptive spike filter is used to remove the outliers from the 11 signal profiles (X) of 5 km horizontal resolution occurring inside each calibration sample region (55 km horizontally for both versions and 30-34 km in V3 and 36-39 km in V4 in the vertical direction) beyond a low and high threshold. The thresholds are determined by the expected molecular signal and the uncertainties from the random noise in the measurement process (Powell et al., 2009). In order to take care of the generally lower signals at the raised calibration altitudes in the new V4 scheme, the low and high threshold values of this uncertainty were adjusted so as to eliminate not more than about 0.15% of the data at both ends.

The valid data segments from the first step are further filtered for large excursions of signal values in the second step of data filtering by estimating the noise to signal ratio (NSR). The NSR is defined as the ratio of the standard deviation and the mean value of all the valid signals and the calculated NSR is compared against an empirical threshold value. If the NSR value estimated from the valid signal profiles is less than the threshold, then the mean profile from the valid signals is constructed (“calibration-ready”). For V4, this step necessitated some careful consideration, since retaining the NSR threshold values used in the V3 tended to preferentially take out the low signal



with high noise (high NSR) data at 36-39 km region thus leading to unrealistically high calibration coefficients. **Figure 3** shows the NSR thresholds (median + 5 median absolute distance) used in V4 as a function of the granule elapsed time (function of latitude). They also vary from month to month to take care of seasonal variation in the noise background. An objective criterion was used to choose these values which minimize the difference in mean calibration coefficients over the SAA region and the non-SAA region within the same latitude band.

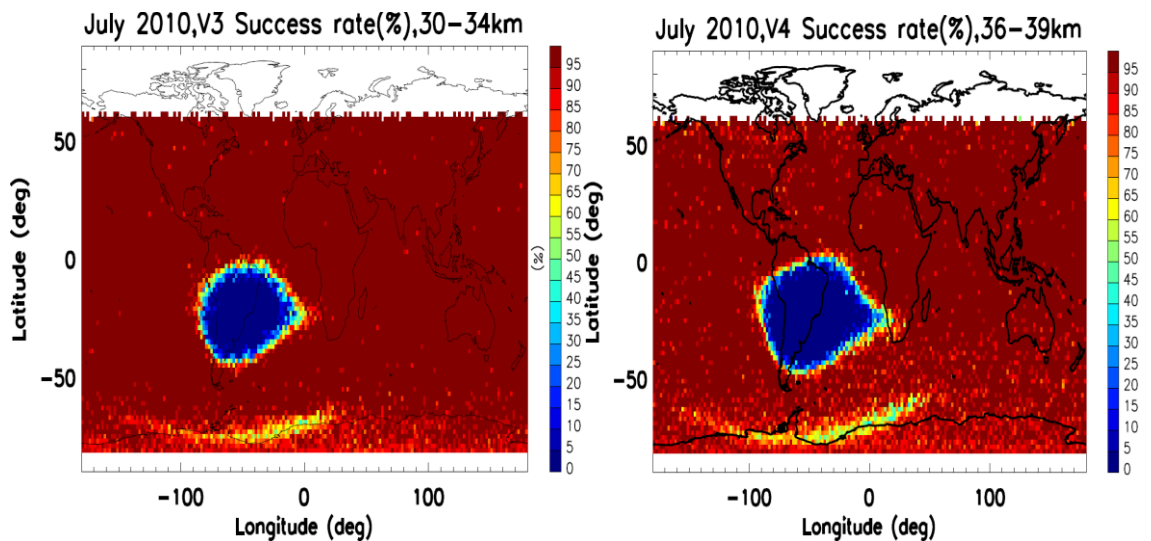


**Figure 3.** The NSR thresholds employed in V4 algorithm for various months as a function of granule elapsed time.

In the third step, the adaptive filter is once again applied but to the mean of the “calibration-ready” profile. If the latter passes this test, then it is used for calculation of the calibration coefficient using equation (1) for the 55 km calibration sample region ( the minimum horizontal distance over which CALIOP collects data uniformly from all the three instruments onboard CALIPSO is called a Payload Data Acquisition Cycle, PDAC and is equal to 55 km). The basic

calibration algorithm over a single PDAC with the new spike filter as mentioned above is similar in both V3 and V4. Further details with examples of the actual filtering and the mathematical basis for computation of the calibration coefficient are available in Powell et al. (2009).

An estimate of the efficiency of the new calibration algorithm may be obtained from the calibration success rate, which is just the ratio of the number of successful calibrations and the attempted calibrations within a specified area.



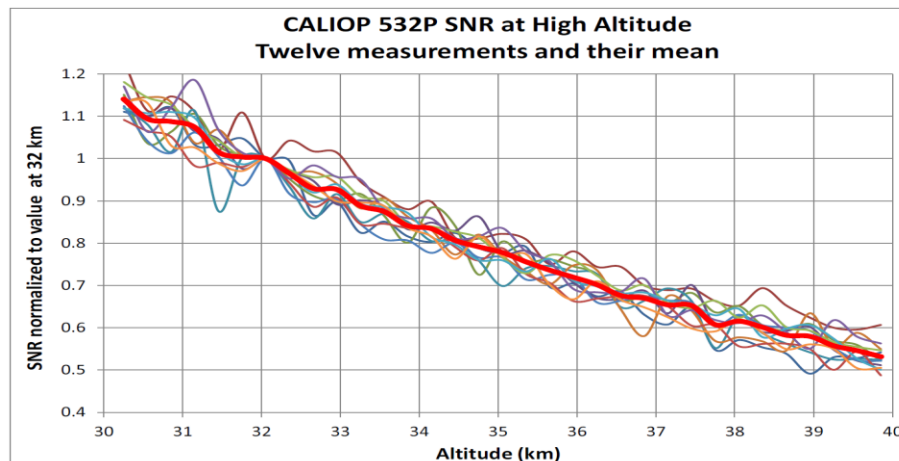
**Figure 4.** Spatial distribution of the calibration success rates for V3 and V4 for the month of July 2010. The data are binned in  $2^{\circ} \times 2^{\circ}$  in latitude and longitude.

**Figure 4** shows the mean calibration success rate in percentage of the attempted calibration for the month of July 2010 for V3 and V4. Both the versions have broadly similar calibration success rates over the globe, with somewhat more noise in V4, as may be expected. Over most of the globe, the success rate is over 90% in both versions. However significantly lower success rates (in blue) occur over the SAA region mentioned above. This is the region where the adaptive filter removes a significant number of calibration profiles leading to the lower success rates. The success rate

also falls significantly over Antarctica and its vicinity with the V4 calibration success rate being somewhat lower than in V3, once again indicating the harsh radiation environment over this area, which affects the SNR particularly at higher altitudes (Hunt et al., 2009).

## 2.4 The new averaging scheme

5           The calibration coefficients obtained over individual PDACs as described above are further smoothed along the orbital track to remove noise. In V3 this smoothing was done over 27 PDACs by computing running averages, covering a distance of 1485 km and leading to the final calibration coefficients for the 532 nm parallel channel. While raising the molecular normalization region to 36-39 km in V4 will clearly lead to better calibration in terms of significant reduction of aerosol  
10   contamination, we have to now deal with a significantly reduced SNR because of reduced molecular density. The SNR from CALIOP measurements has been simulated using the FREESIM simulation package (Hunt, 2012, NASA Langley internal report). In the V3 calibration algorithm (30-34 km), the smoothing of the calibration coefficients over 27 PDACs (1485 km) resulted in a simulated SNR of 57.1 for the molecular backscatter signals. If the same level of smoothing were  
15   to be retained in the new calibration region of 36-39 km, then the simulated SNR drops significantly to 32.1.

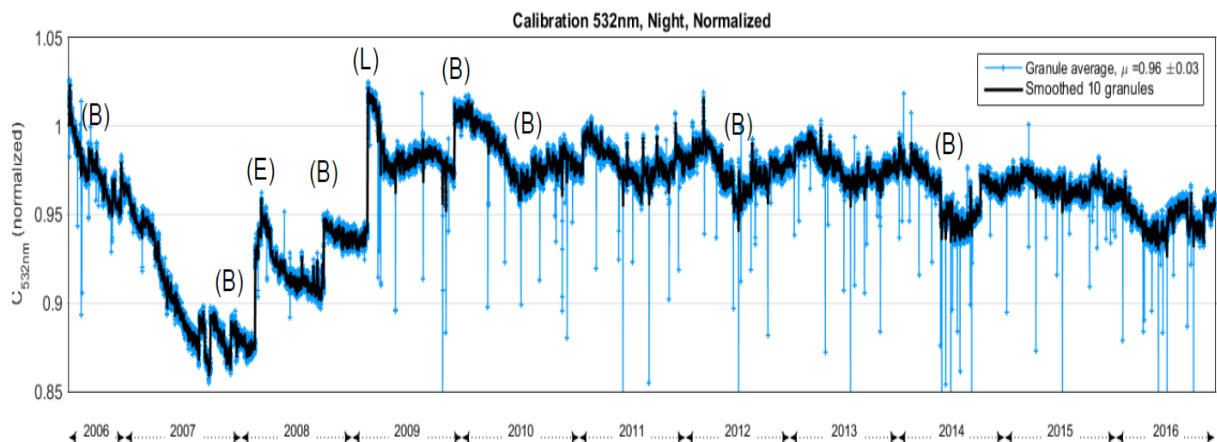


**Figure 5.** 12 SNR profiles from CALIOP measurements representing various latitudes and seasons. The thick red line is the mean profile.

This sharp drop in simulated SNR is consistent with the measured SNR profiles as can be seen in **Figure 5**, where we have shown 12 measured SNR profiles from CALIOP representing the different seasons and a large range of latitudes over 2009-2012. The values were normalized to the value at 32 km. In order to recover the same level of SNR as V3, the simulations indicate that the data has to be smoothed over at least 4710 km or 86 PDACs. An examination of the calibration coefficients from consecutive orbits showed no significant variability from day to day indicating that no loss of accuracy will occur by taking average over multiple orbits. On the other hand it would be desirable to reduce averaging distance over the same orbit. Therefore it was decided to average the calibration coefficients over 11 consecutive orbits with 11 PDACs from each orbit (605 km along track over each orbit) for the new calibration (i.e. 121 PDACs in all covering a distance of 6655 km).

### 3. Assessment of CALIOP V4 calibration

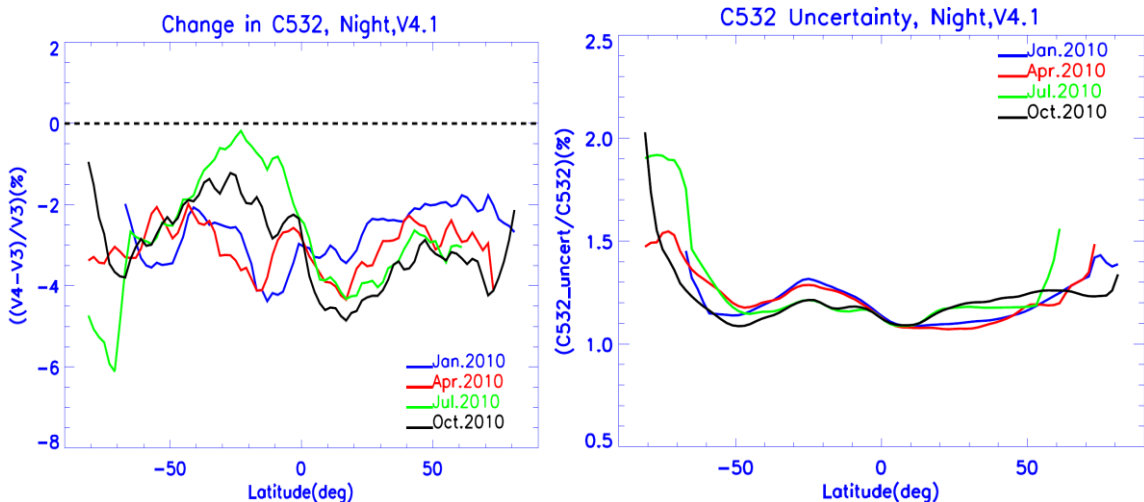
With these revisions in the averaging scheme and the spike filter, the calibration of the parallel channel nighttime 532 nm measurements was carried out for V4.



**Figure 6.** The time series of the V4 532 nm CALIOP nighttime parallel calibration coefficient. The values have been normalized by the initial value ( $6.1483 \times 10^{10}$ ). The letters represent the various instrument events that affect the calibration: (B) -- boresight alignment, (E) – etalon temperature adjustment, (L) – laser switch.

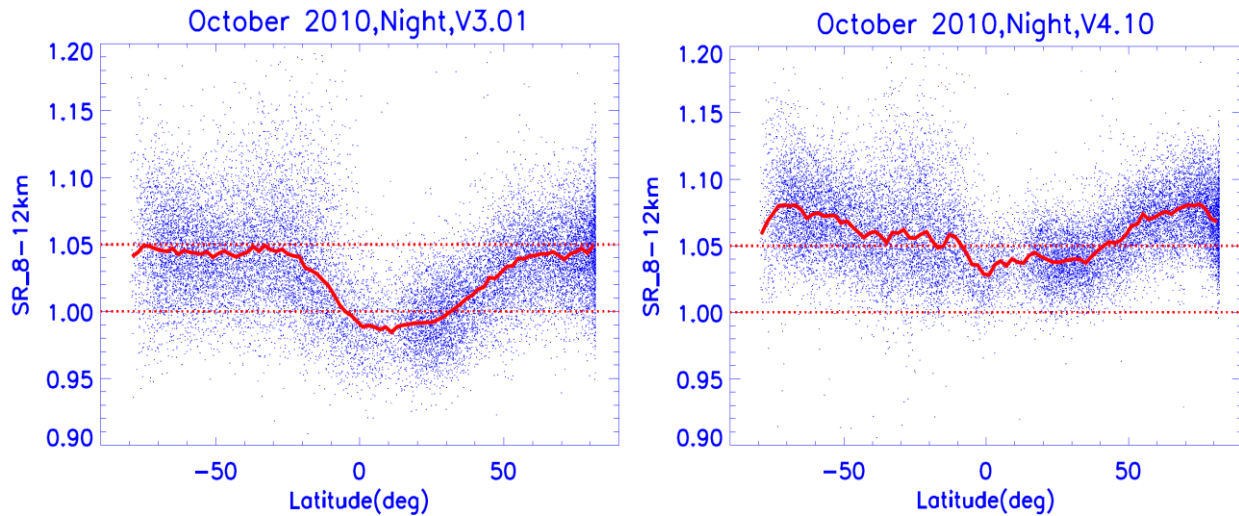
5 **Figure 6** shows the time series of the V4 calibration coefficient over the entire mission period from 2006 through 2016. The granule average values of the coefficients (in blue) have been smoothed over 10 granules (in thick black). Over short term, the sharp upward revisions in calibration mostly correspond to the boresight alignment and etalon scan procedures. These procedures take place periodically. Apart from these, there were two significant one-time events  
 10 that took place. Firstly, the primary laser started showing signs of degradation and was replaced by the second laser in March 2009. Secondly, the laser pointing angle was changed from 0.3 degree to 3.0 degree in November 2007. The longer term downward trends in the calibration coefficient values likely represent component degradation (as may have occurred during the operation of the  
 15 first laser), boresight misalignment and etalon mismatch (Hunt et al., 2009).

15 **3.1. Overall differences between V3 and V4 calibration**



**Figure 7. a)** The fractional change from V3 to V4 in the zonally averaged 532 nm calibration coefficient for 4 months in 2010 (left panel) and **b)** the corresponding zonally averaged relative uncertainty in the calibration coefficient for the same months (right panel).

5 **Figure 7a** shows the zonal mean distribution of the fractional change in the 532 nm nighttime calibration coefficient from V3 to V4 for the months of January, April, July and October 2010 representing the four seasons. The calibration coefficient in V4 obtained from measurements at 36-39 km decreases by 2-3% on average as compared to the calibration coefficients derived at 30-34 km in V3 as may be expected because of negligibly low aerosol contamination at 36-39 km as  
10 shown in **Figure 2**. There is some seasonal variation in the amount of change from V3 to V4 most notably at the southern tropics. Seasonal and inter annual variations in the calibration change may be expected as the aerosol loading at 30-34 km responds to the stratospheric dynamics. One important criterion for improving the calibration in V4 was to retain the same level of the estimated relative random uncertainty in the calibration coefficient. **Figure 7b** shows the zonal mean relative  
15 uncertainty in the calibration coefficient in V3 and V4 for the four months corresponding to **Figure 7a**. Overall the random uncertainty is less than 2-3% with higher values over the SAA region and near the poles because of the noise in the measurements in these regions. This is of the same order of uncertainty as in V3.



**Figure 8.** Clear air scattering ratios at 8-12 km as a function of latitude for the month of October 2010 for V3 (left panel) and V4 (right panel). The thick red lines are median values calculated over  $2^\circ$  latitude bins.

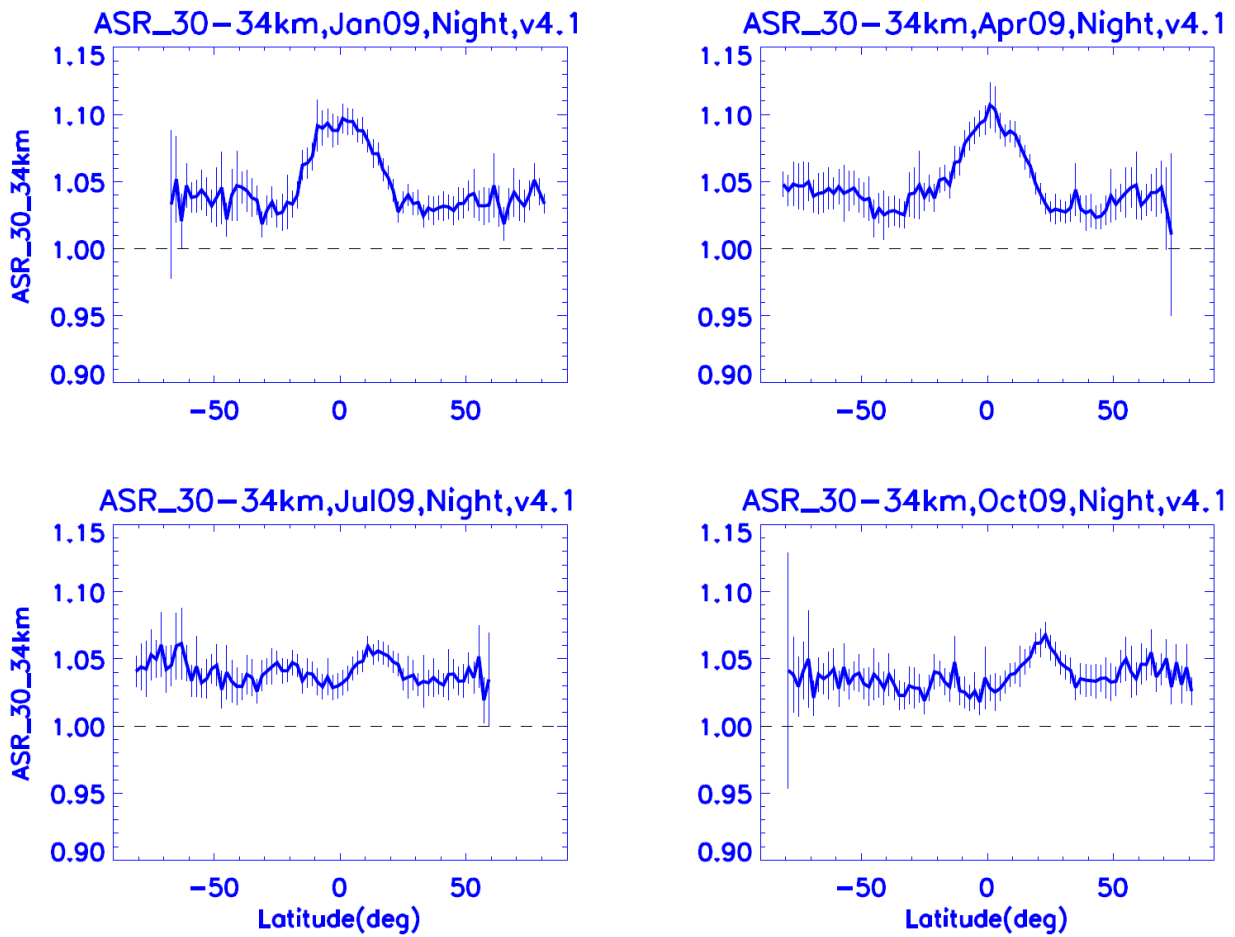
5 We will now use the attenuated scattering ratios defined in section 2 to assess the new calibration. One of the important signatures indicating less than optimum calibration in V3 532 nm nighttime data was a characteristic dip in SR values in the tropics calculated for clear air conditions over 8-12 km region (Powell et al., 2009). **Figure 8** shows the “clear air” scattering ratios computed between 8-12 km for V3 (left panel) and V4 (right panel) for October 2010. Each point in this scatter plot represents a 200 km segment along the orbit which has been determined to be “clear air” (i.e. no cloud or aerosol layers) using the corresponding V4 level 2 cloud and aerosol products and the red curves are median values over  $2^\circ$  latitude bins. Note that polar stratospheric clouds (PSC) were additionally cleared along with the tropospheric clouds and aerosols for this plot using the currently available version (V1.0) of the PSC product which is however based on the CALIOP

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15 V3 level 2 data. The forthcoming PSC V2.0 product will incorporate V4 level 2 information and MERRA 2 meteorology. As can be seen in **Figure 8**, the strong dip in the tropics seen in V3 data

no longer appears in V4 with relatively very few points showing  $SR < 1$ . This along with the general meridional uniformity of “clear air” SR indicates a significantly improved calibration in V4 of CALIOP data. It should be noted that there may be tenuous particulate loading in the 8-12 km region which might be below the layer detection threshold of CALIOP, which will nonetheless

5 show up in scattering ratios with SR values in excess of the expected clear air SRs ( $\sim 1$ ).



**Figure 9.** Zonally and vertically (over 30-34 km) averaged SR calculated from V4 CALIOP attenuated backscatter data for January, April, July and October 2009. Data over SAA region were not included and are binned over  $2^\circ$  in latitude (with at least 50 points within the latitude bin).

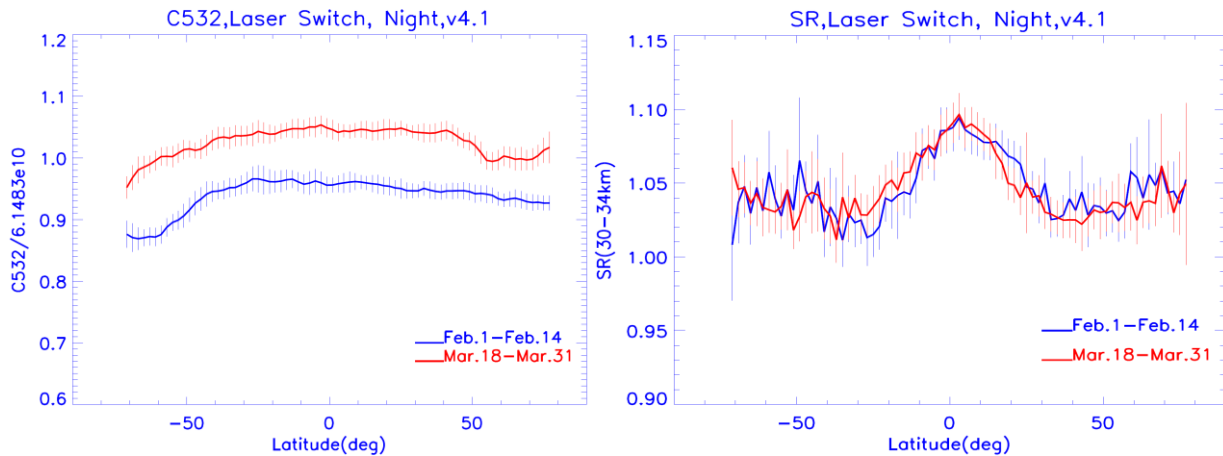


The old calibration altitude range of 30-34 km presents a useful region for calibration assessment in the new version, since SR was essentially forced to 1 in this region in V3 and should be different in V4. **Figure 9** shows the zonal mean distribution of SR averaged over 30-34 km as estimated from the level 1B files from V4 for January, April, July and October 2009 representing the four seasons. The SR values at 30-34 km in V4 varies between ~3%-10% in all the cases with significant seasonal variations while in V3 these values were all forced to one.

### 3.2. Effects of instrumental changes on version 4.10 calibration

As shown in **Figure 6**, several instrumental changes have taken place in the CALIOP lidar since the beginning of the mission. Each of these configuration changes results in a corresponding change in the calibration coefficient. A good metric for evaluating the calibration procedure is to ensure that these changes in calibration should leave the science data unaffected. In this section we assess this aspect of the V4 calibration.

#### 3.2.1. Laser switch

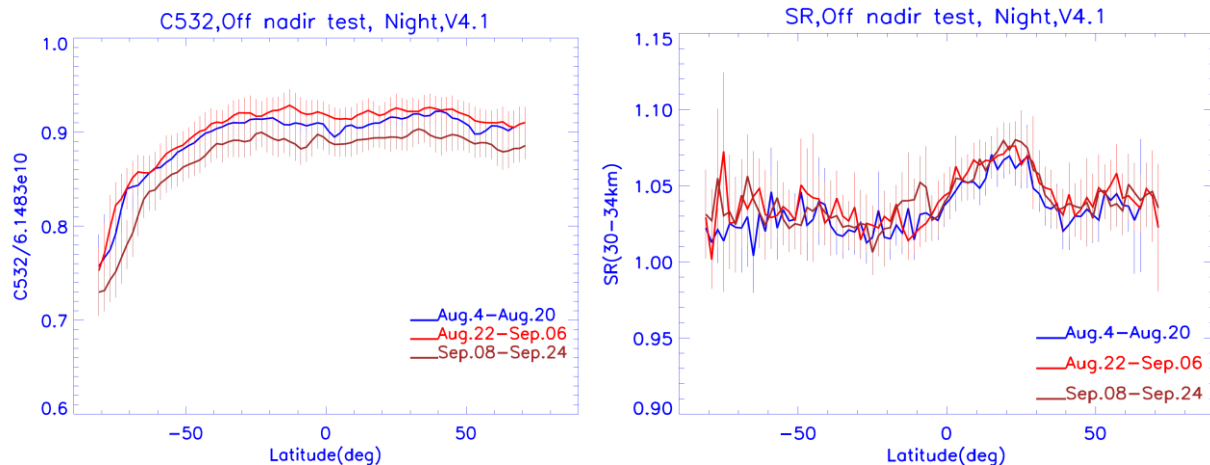


**Figure 10. a)** Zonally averaged normalized 532 nm calibration coefficient and standard deviations, **b)** SR at 30-34 km calculated using 2 weeks worth of data before (February 1-

14, 2009) and after (March 18-31,2009) the laser switch. SR profiles were calculated over 2° latitude intervals from each granule and then averaged over all granules for the latitude bin (with a minimum number of 50 SR profiles in each bin). Data over SAA were not included.

5 There are two lasers onboard CALIPSO and the CALIOP data production in June 2006 was started with the primary laser (called laser 2). However the canister housing the optics and the high voltage components gradually lost pressure from a leak and the laser started showing anomalous behavior presumably resulting from coronal discharge at low pressures. As a result, the primary laser was turned off on February 16, 2009 and the backup laser (called laser 1) was subsequently activated  
 10 on March 12, 2009 which has since been continuously operating. This is the largest configuration change so far in the mission and led to a very large concomitant change in the calibration coefficients as can be seen in **Figure 10** which shows (left panel) the zonal mean calibration coefficients for two periods representing pre-switch (February 1-14) and post-switch (March 18-31) periods. However the zonal mean SR values (right panel) computed for these two periods agree  
 15 quite well and clearly indicates that the calibration algorithm has been correctly implemented.

### 3.2.2. Off-nadir test



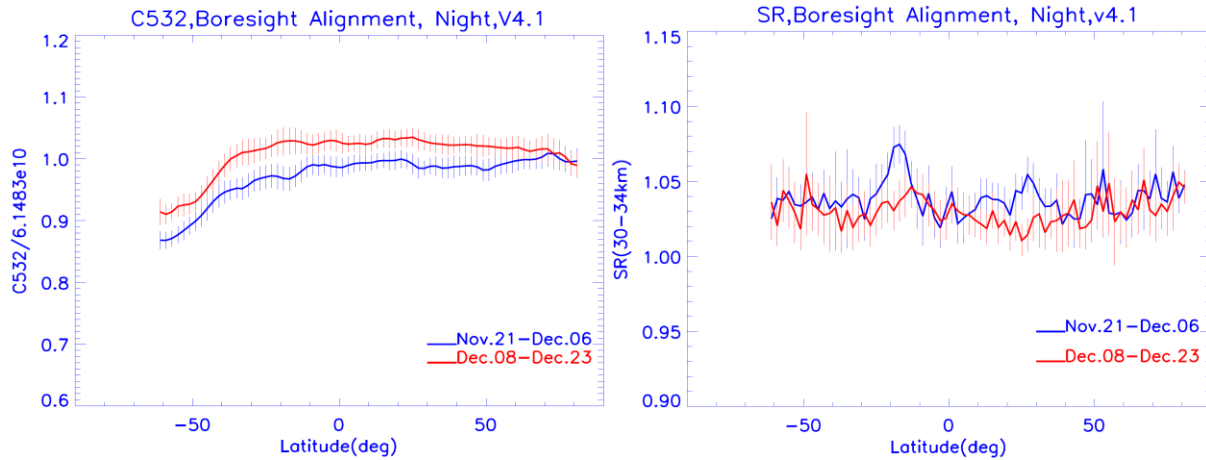
**Figure 11.** Same as in **Figure 10** using data before (August 4-20, 2007), during (August 22-September 6, 2007) and after (September 8-24, 2007) the off-nadir laser pointing test.

Another significant instrument event took place in November 2007 when the pointing angle of the laser was changed from 0.3 degree to 3.0 degree in order to avoid the effects of specular reflections (Hunt et al., 2009). An advanced test of this change was carried out between August 22 and September 6, 2007 when the pointing angle was held at 3 degree and changed back to 0.3 degree pending final change in November 2007. **Figure 11a** (left panel) shows the normalized calibration coefficients before the test (August 4 - August 20, 2007), during the test (August 22 – September 6, 2007) and after the test (September 8 – September 24, 2007). Although not as large as the change from the laser switch, significant changes in the calibration coefficients can still be discerned among the curves. Note that the calibration coefficients do not exactly revert back to the pre-test values and are significantly lower. This is because this test took place when the primary laser was still operational and the calibration coefficient was continuously decreasing during this period. However despite this, the zonal mean SR values (right panel) at 30-34 km are all essentially coincident thus testifying to the robustness of the calibration algorithm.

### **3.2.3. Boresight alignment**

The alignment between the CALIOP transmitter and the receiver is maintained by a boresight alignment mechanism that adjusts the laser pointing direction to maximize the return signal and is carried out occasionally. A large boresight alignment took place on December 7, 2009. **Figure 12** shows zonally averaged calibration coefficients before (November 21- December 6, 2009) and after (December 8 – December 23, 2009) the boresight alignment. The calibration coefficients changed significantly in response to the event. However as can be seen in the right

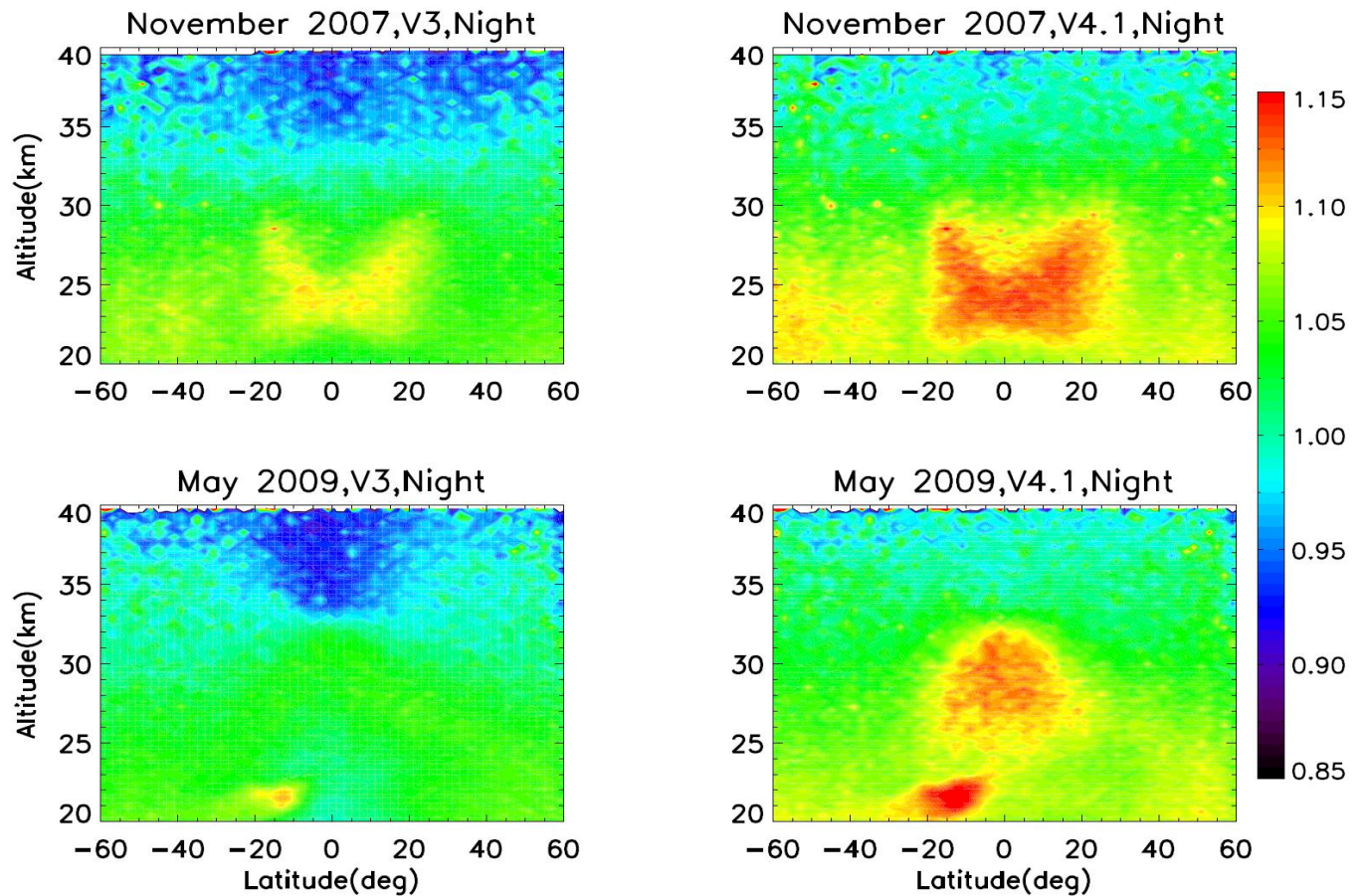
panel below, the scattering ratio didn't change significantly before and after the events once again indicating a proper implementation of the new calibration algorithm.



5 **Figure 12.** Same as in **Figure 10** using data **a**) before (November 21-December 6, 2009) and **b**) after (December 8-23, 2009) the boresight alignment procedure on December 7, 2009.

### 3.3 Impacts on science: stratospheric aerosol

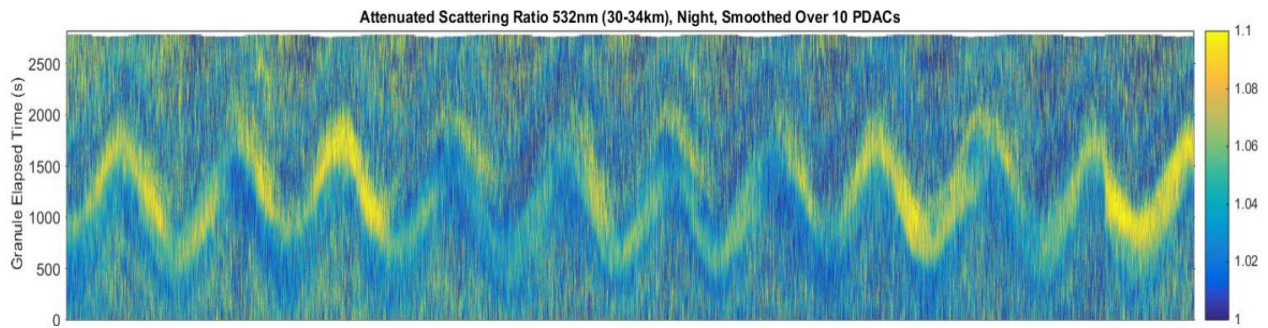
As shown above, the new calibration coefficients in V4 leads to a generally upward revision of the  
 10 level 1 attenuated backscatter coefficients by 3-6% depending upon the location and season. In particular, **Figure 9** shows that variations in aerosol loading at the stratospheric altitudes may be robustly captured in the new data. This is illustrated further in **Figure 13**, which shows the zonally averaged height latitude cross sections of SR in November 2007 and May 2009 for both V3 and V4.



**Figure 13.** Height latitude cross sections of the attenuated scattering ratio calculated using V3 and V4 level 1 data for November 2007 (top two panels) and for May 2009 (bottom two panels).

- 5 In both these months, distinct structures can be observed in the stratospheric regions between 20 km and 30 km in the tropics which are likely linked to the quasi-biennial oscillations (QBO) of lower stratospheric winds between about 20-35 km. In November 2007, dominant westerly shear prevailed in the stratosphere (monthly mean zonal wind at Singapore at 10 hPa =  $18 \text{ ms}^{-1}$ ) leading to a characteristic double horn structure in the tropical stratospheric aerosol distribution (Trepte  
 10 and Hitchman, 1992). In the V3 map (top left) this structure can be seen only partially, while it is much more prominent and clear in the V4 map (top right). On the other hand, dominant easterly

shear prevailed in the stratosphere in May 2009 (monthly mean zonal wind at Singapore at 10 hPa =  $-34.2 \text{ ms}^{-1}$ ) during which aerosol lofting is expected to take place in the tropics and lateral transport is inhibited (Trepte and Hitchman, 1992). The aerosol lofting is not seen in the V3 map (bottom left), but is quite clearly observed in the V4 map (bottom right). This demonstrates that the V4 CALIOP data can provide important and robust information in the stratosphere. This is further seen in the time series of SR at 30-34 km from 2006-2016 (**Figure 14**). A CALIOP stratospheric aerosol product is currently under development which exploits this improved calibration.



**Figure 14.** Scattering ratio at 30-34 km as a function of time and granule elapsed time (function of latitude) for the period June 2006 through 2016. The data has been smoothed over 10 PDACs.

#### 4.0 Initial validation of the version 4.10 calibration

##### 4.1. Comparison with HSRL

The airborne High Spectral Resolution Lidar (HSRL) developed at NASA Langley Research Center has been used over the years for validation of CALIOP lidar calibration through coincident underflights (Hair et al., 2008). The HSRL provides internally calibrated attenuated backscatter

measurements at 532 nm, thus avoiding the issues about aerosol contamination at calibration altitudes for space borne lidars and are very accurate, ~1-2% (Rogers et al., 2011).

<b>Mission</b>	<b>Date Range</b>	<b>Number of CALIOP flights</b>
CC-VEX	21 Jun 2006 - 10 Aug 2006	5
GOMACCS	17 Sep 2006 - 24 Sep 2006	2
CALIPSO Validation 2007	26 Jan 2007	1
CALIPSO Calibration 2009	22 Jan 2009 - 17 Apr 2009	11
CALIPSO Calibration 2010	10 Apr 2010 - 22 Apr 2010	5
Caribbean	22 Aug 2010 - 26 Aug 2010	3
DISCOVER-AQ	19 Mar 2011 - 02 Apr 2011	3
CALIPSO Calibration 2012	26 Mar 2012 - 30 Mar 2012	2
Bermuda	12 Jun 2014 - 16 Jun 2014	3
<b>Total</b>		<b>35</b>

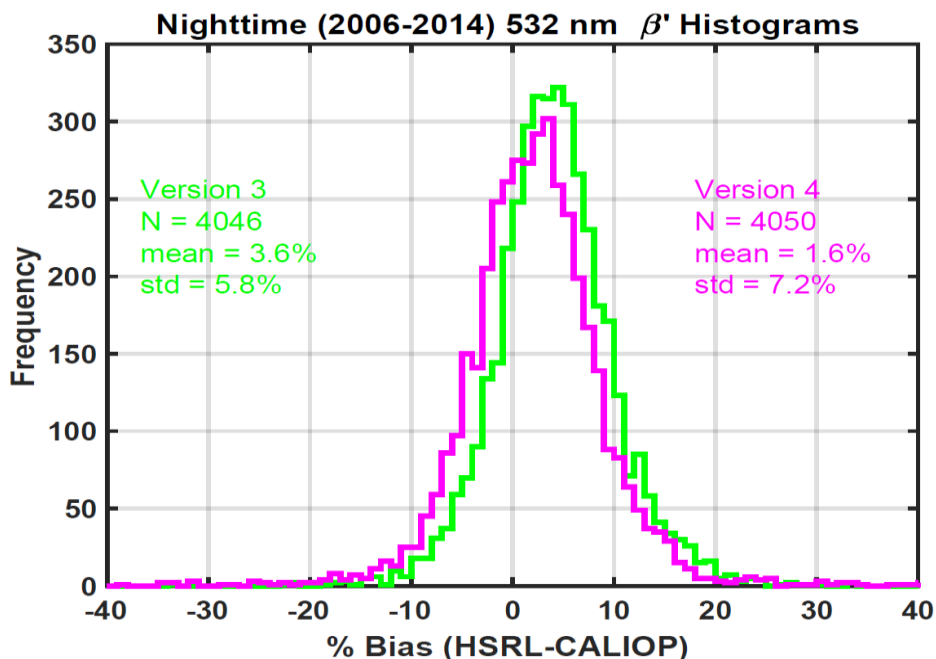
**Table 1.** Dates and missions under which HSRL nighttime flights were conducted.

5 Table 1 lists the different field missions and the dates when the HSRL underflights took place during nighttime between June 2006 and June 2014. Some of these flights were solely for the purpose of CALIPSO validation activity and some were under the auspices of a more general field mission with other objectives. A total of 35 nighttime flights were used for comparison with the coincident CALIOP measurements. For comparison with CALIOP, the total attenuated backscatter  
10 estimated from HSRL for “clear-air” regions are first corrected for the molecular attenuation between the HSRL reference altitude (~1.5 – 2 km below the flight altitude) and the CALIOP altitude. Difference profiles between HSRL and CALIOP are then calculated using the equation:

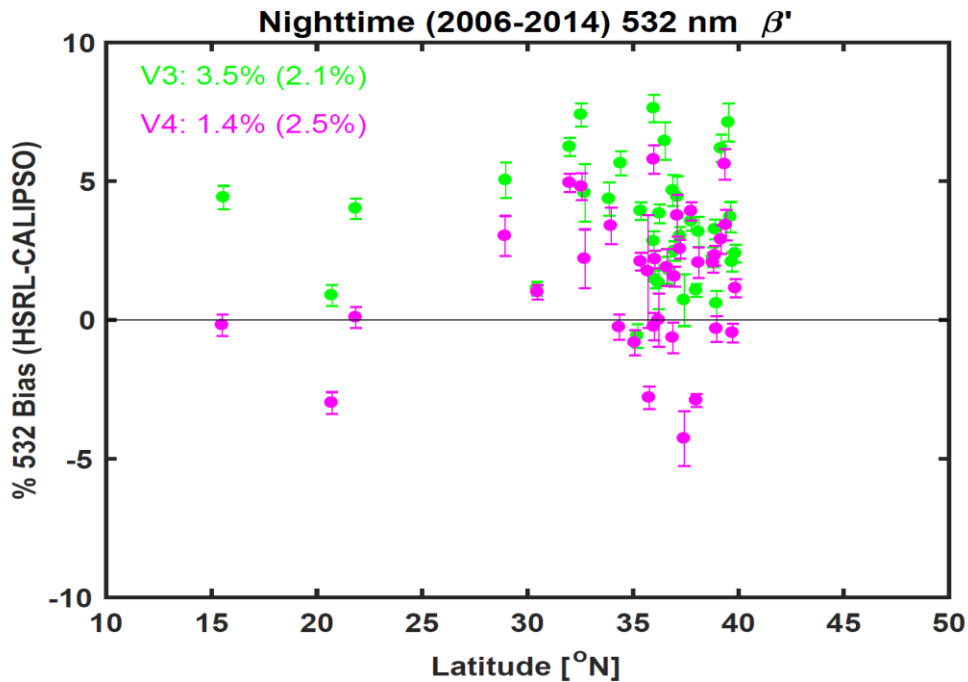
$$\Delta C(r) = \frac{\beta'_{HSRL}(r) - \beta'_{CALIOP}(r)}{\beta'_{HSRL}(r)} \quad (4)$$



where,  $\beta'_{HSRL}(r)$  is the mean of the coincident and cloud-free total attenuated backscatter from HSRL at range  $r$  and referenced to CALIOP altitude, and  $\beta'_{CALIOP}(r)$  is the corresponding mean of total attenuated backscatter from CALIOP at range  $r$ . For further details of the comparison methodology, the reader is referred to Rogers et al. (2011). A single difference value was estimated for each HSRL coincident underflight by taking average over the horizontal and vertical dimensions of the clear-air region. **Figure 15a** shows the histogram of these differences and essentially represents the assessment of the CALIOP calibration. The distributions are shown for both V3 and V4. The mean difference between HSRL and CALIOP was 3.6% using V3 calibration, which has now been reduced significantly to 1.6% in V4, indicating a much improved calibration for CALIOP V4 algorithm. Most of the flights took place in the northern mid latitudes between 30°N-40°N (**Figure 15b**). Although the comparison covers only a limited latitude range, no obvious latitude dependence can be discerned. This figure shows the corresponding mean differences from V3 to V4 for the various flights. Most of differences from the individual flights have decreased significantly, with the exception of a few outliers.







**Figure 15. a)** Distributions of the average differences between HSRL and CALIOP of the 532 nm total attenuated backscatter in the nighttime clear air regions of coincidence and **b)** the differences as a function of latitude. V3 data are shown in green while the V4 data are shown in magenta. N in a) represents the total number of coincidence profiles. The error bars in b) represent the standard error of the mean.

#### 4.2. Comparison with NDACC lidar at Dumont d’Urville

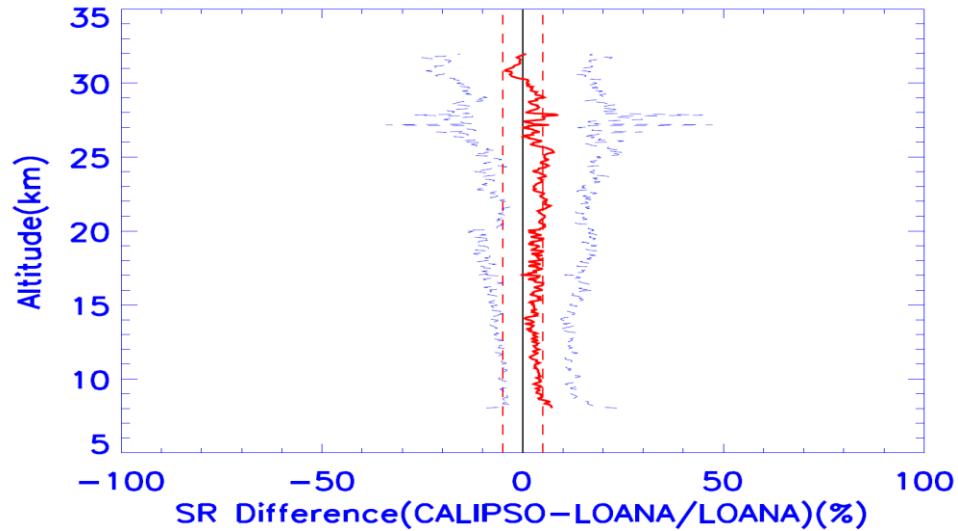
Ground based data from a number of lidars are available through the Network for the Detection of Atmospheric Composition Change (NDACC). For this initial validation and in view of the noisy environment over Antarctica and the availability of a large number of comparable backscatter profiles, we have selected to present the comparison between CALIOP and the Lidar for Ozone and Aerosols for NDACC in Antarctica (LOANA) at Dumont d’Urville, located at the French Antarctic station ( $67^{\circ}$ S,  $140^{\circ}$ E). Correlative data from LOANA are available for most of the years when CALIPSO has been functional thus offering opportunities for a robust comparison. Aerosol

and PSC measurements are carried out using this lidar at night between 8 km and 32 km and in clear sky conditions at 532 nm and 1064 nm, the vertical resolution of the profiles being 60 m (David et al., 2012). The lidar signals in the parallel channel are averaged over 5 minutes to reduce the noise level. Scattering ratio profiles are calculated using the Klett method with an uncertainty in SR between 5-10% from various sources. The molecular densities used in the calculations are obtained from daily radiosonde launches.

For the comparison, we first check each lidar SR profile available from LOANA database. If the maximum value of the SR profile is less than 1.5, then it is considered to be a “clear air” profile and is selected for comparison. All CALIOP data falling within a 2°x2° in latitude and longitude coincidence box is used to select the CALIOP profiles for the same day and year. Subsequently, the CALIOP attenuated backscatter profiles are filtered for cloud and aerosol layers above 8 km using V4 level 2 data as well as PSCs using V1.0 CALIPSO PSC product. All the clear air CALIOP profiles from within the coincidence box for a specific day are then averaged and SR profiles are calculated after rejecting SR values above 1.5, to be consistent with the LOANA “clear-air” profiles. The CALIOP profiles are then interpolated to the LOANA altitude grid and compared with the LOANA profile for that day (averaged if multiple profiles were available for a single day) yielding difference profiles:

$$\Delta = 100. \frac{(SR_{CALIOP} - SR_{LOANA})}{SR_{LOANA}} \quad (5)$$

A total of 94 days worth of data were compared covering all available LOANA measurements from 2006 to 2014 varying from a minimum of 3 days in 2009 to a maximum of 18 days in 2014.



**Figure 16.** Profile of the mean difference in SR from CALIOP and LOANA lidars for clear air conditions above 8 km. Coincident data from 2007 through 2014 have been used for this comparison. The red dashed lines demarcate 5% difference.

5 **Figure 16** shows the mean difference profile obtained from this comparison. The agreement between the two instruments is within 5% on average. Given the noise considerations, which are particularly high at Antarctic latitudes (Hunt et al., 2009) and all the other uncertainties from the different normalization procedures adopted by the two instruments, this agreement using a large number of samples confirms the significantly improved calibration of CALIPSO version 4 level 1  
 10 data.

## 5.0 Conclusions.

Accurate calibration of the CALIOP nighttime 532 nm measurements is the most important element in ensuring robustness of the CALIOP data products since all the other measurements derive their calibration from this. In the V4 algorithm, the calibration altitude for the nighttime  
 15 parallel channel has been raised from 30-34 km to 36-39 km which ensures no or minimal

contamination from stratospheric aerosols for the molecular normalization procedure. We have presented the salient features of the new calibration procedure and pointed out the improvements in the V4 data arising from this new calibration. The inconsistencies in the V3 data owing to the old calibration have now been resolved. The uncertainties in the V4 calibration are of the same order as in V3 and the calibration correctly adjusts to the periodic instrument changes like boresight alignments, leaving the science data unaffected. The improved calibration also lends itself to a robust representation of stratospheric aerosols. The initial validation of the calibration using the coincident HSRL measurements at northern mid latitudes indicates an agreement of <1% suggesting a robust calibration. Comparison with a ground based lidar at Antarctica also gives good agreement (within 5%). Overall a significant improvement in CALIOP primary calibration has been achieved in V4 and this should result in a corresponding improvement in the level 2 CALIOP products downstream.

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